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13. ABSTRACT (Maximum 200 words)

The grant supported research on motion, shape, geometry, and object recognition. Work in the first area dealt with geometric and probabilistic models for understanding image sequences. In the second area, growth and migration models for the generation and evolution of shapes were developed. The third area included a wide variety of basic geometrical studies. The fourth area dealt with an integrated approach to model-based object segmentation and recognition, and with the recognition of object functionality. In addition, annual, subject-indexed bibliographies of the literature on computer vision and image analysis—about 1500 references per year—were compiled and published.

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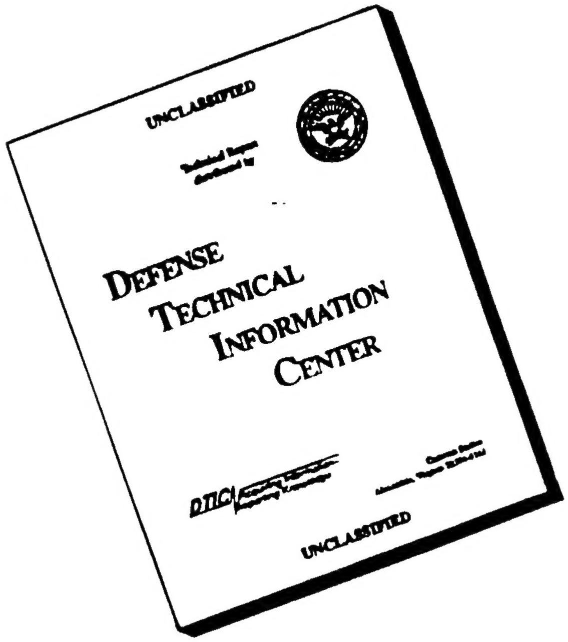

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FINAL TECHNICAL REPORT
on Grant F49620-93-1-0039
"Domain-Specific Models in Computer Vision"

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Period covered: 15 November 1992 - 14 May 1996

June 24, 1996

The grant supported research leading to five Ph.D. dissertations (a sixth is still in progress) and 26 journal publications. The research conducted under the grant has focused on the following areas:

1. **Motion:** Geometric and probabilistic models for understanding image sequences were investigated by two Ph.D. students, Mohamed Abdel-Mottaleb (now with North American Philips Corp.) and Zoran Duric (now with George Mason University). Maximum A Posteriori algorithms were developed for estimating the motion of a camera system by analysis of optical flow. Robust algorithms were developed for estimating bounds on the rate of approach of a moving sensor system to a surface by analyzing the apparent deformations of surface contours. Real-time algorithms were developed for smoothing ("selectively stabilizing") the image sequences obtained by a camera carried by a vehicle moving over rugged terrain.

2. **Shape:** Growth and migration models for the generation and evolution of shapes were developed by two Ph.D. students, Scott Thompson (now with Tekamah Corp.) and Sandor Fejes (now a postdoc at the University). Digital growth processes, operating on a regular grid, were developed that can generate large classes of smooth shapes, using mechanisms involving time-delayed growth. A class of processes was developed for modifying shapes using iterated neighborhood averaging; these processes behave very similarly to PDE-based proceses of curvature-sensitive contour evolution.

3. **Geometry:** Basic geometrical studies conducted under the grant dealt with "well-composed" (i.e., adequately digitized) sets, for which the algorithms of digital geometry become greatly simplified; the invertibility of Hough transforms; characterization of the boundaries of convex sets (a problem posed over 30 years ago, but not previously solved); fuzzy geometric figures; robust circle estimation; geodesic convexity; geometric properties of sets of lines; the calculus of discrete (digital) functions; and "tame" functions which are piecewise convex and concave.

4. **Object Recognition:** An intergrated approach to model-based object segmentation and recognition was the subject of the Ph.D. dissertation of Noah Friedland (now with Lockheed-Martin Corp.). The recognition of object functionality was also studied for both static objects, using models based on volumetric primitives, and for objects in motion, using models for the flow patterns generated when primitive object parts move in simple ways relative to their natural axes.

5. Annual, subject-indexed bibliographies of the literature on computer vision and image analysis—about 1500 references per year—were compiled and published.

Appendix A: Abstracts of Technical Reports

1. Mohamed Abdel-Mottaleb, Rama Chellappa and Azriel Rosenfeld, "Binocular Motion Stereo using MAP Estimation." CAR-TR-650, CS-TR-2998, November 1992.

ABSTRACT: We present an algorithm for fusing monocular and stereo cues to get robust estimates of both motion and structure. Our algorithm assumes the motion to be along a smooth trajectory and the sequence of images to be dense, so that the displacement between successive frames obtained by each camera is at most n pixels, where typically $n = 2$. The algorithm starts by calculating the instantaneous FOE (focus of expansion). Knowing the FOE we calculate a MAP estimate of the displacement at each pixel and an associated confidence measure. Using the displacement estimates we calculate a relative depth map from one of the two frame sequences. By calculating the disparities at some feature points and using information about their relative depths we compute the instantaneous component of velocity in the direction perpendicular to the image plane (the Z direction). Using this information a depth map is calculated; this depth map is then used to derive a prior probability distribution for disparity that is used in matching the two frames of the stereo pairs. We use this method to estimate the disparity at each pixel independently; no assumptions about smoothness are used. Experimental results on a real image sequence are given.

2. Azriel Rosenfeld, "Image Analysis and Computer Vision: 1992." CAR-TR-653, CS-TR-3015, January 1993.

ABSTRACT: This paper presents a bibliography of nearly 1900 references related to computer vision and image analysis, arranged by subject matter. The topics covered include architectures; computational techniques; feature detection and segmentation; image analysis; two-dimensional shape; pattern; color and texture; matching and stereo; three-dimensional recovery and analysis; three-dimensional shape; and motion. A few references are also given on related topics, such as geometry, graphics, image input/output and coding, image processing, optical processing, visual perception, neural nets, pattern recognition, and artificial intelligence, as well as on applications.

3. Scott Thompson and Azriel Rosenfeld, "Discrete Stochastic Growth Models for Two-Dimensional Shapes." CAR-TR-656, CS-TR-3023, January 1993.

ABSTRACT: Discrete models for growth of a shape from a point on a two-dimensional Cartesian grid are described. By *growth* is meant an accretionary process occurring at the boundary of the shape. Three types of growth models are discussed: deterministic (periodic), probabilistic (stochastic), and probabilistic mixing of deterministic processes. Each type is defined and illustrated with examples. It is shown that probabilistically mixing deterministic processes can produce smooth isotropic or elongated regions, concavities, and protrusions. The paper emphasizes empirical results; analytical studies are in progress.

4. Noah S. Friedland, "An Integrated Approach to Object Recognition." CAR-TR-657, CS-TR-3024, January 1993.

ABSTRACT: A multilevel Markov Random Field (MRF) energy environment has been developed that simultaneously performs delineation, representation and classification of two-dimensional objects by using a global optimization technique. This environment supports a novel multipolar shape representation which establishes a dynamic MRF structure. This structure is initialized as a single-center polar representation, and uses minimum description length tests to determine whether to establish new polar centers. The polar representations at these centers are compared with a database of such representations in order to identify pieces of objects, and the results of these comparisons are used to compile evidence for global object identifications. This method is more robust than conventional multistaged approaches to object recognition because it incorporates all the information about the objects into a single decision process.

5. Longin Latecki, Ulrich Eckhardt and Azriel Rosenfeld, "Well-Composed Sets." CAR-TR-663, CS-TR-3057, April 1993.

ABSTRACT: A special class of subsets of binary digital images called "well-composed sets" will be defined. The sets of this class have very nice topological properties; for example, the Jordan Curve Theorem holds for them, the Euler characteristic is locally computable, and we have only one connectedness relation, since 4- and 8-connectedness are equivalent. This implies that basic algorithms used in computer vision become simpler. There are real advantages in applying thinning algorithms to well-composed sets. Thinning is an internal operation on these sets and the problems with irreducible "thick" sets disappear. Furthermore, we prove that the skeletons obtained are "one point thick" in addition to giving a formal definition of the concept "one point thick". We also show that skeletons can have a graph structure while again defining what this means. There are also practical advantages in applications; in particular, thinning algorithms are faster on well-composed sets.

6. Mohamed Abdel-Mottaleb, Rama Chellappa and Azriel Rosenfeld, "Binocular Motion Stereo with Independently Moving Objects." CAR-TR-679, CS-TR-3106, July 1993.

ABSTRACT: We present an algorithm for estimating both motion and structure from a moving pair of cameras in an environment that contains moving objects. The sequence of images is assumed to be dense so that the displacement between successive frames obtained by each camera is small. We start by calculating the instantaneous FOE (focus of expansion). Knowing the camera motion we calculate an estimate of the displacement at each pixel. Using the displacement estimates we calculate an estimate of the disparity; this estimate will be correct for stationary points but will be wrong for moving objects. We then apply a recursive algorithm for disparity calculation. This algorithm starts by accepting strong matches which are used to restrict the solution space for matches in the next iteration. A byproduct of this algorithm is the detection of moving objects. The motion parameters for the independently

moving objects are then estimated.

7. Azriel Rosenfeld and Isaac Weiss, "A Convex Polygon is Determined by Its Hough Transform." CAR-TR-681, CS-TR-3121, August 1993.

ABSTRACT: A Hough transform maps a set of n collinear line elements in the plane into a spike of height n in a line parameter space ("Hough space"). Evidently, many different patterns of line elements can give rise to the same Hough transform, since collinear line elements can be located anywhere along a line. This note shows that if the line elements constitute the boundary of a convex polygon, the polygon is uniquely determined by the transform; but this is not true for arbitrary nonconvex polygons.

8. Scott Thompson and Azriel Rosenfeld, "Isotropic Growth on a Grid." CAR-TR-686, CS-TR-3139, September 1993.

ABSTRACT: Isotropic growth from a single point on a two-dimensional square grid should generate an increasing sequence of discretized discs. We present a simple probabilistic model for growth on a grid, and discuss a class of parameterizations of the model (called kernels) which we conjectured (in [TR93]) would produce isotropic growth. We disprove this conjecture, but we claim that these kernels produce growth that can be decomposed into isotropic and nonisotropic components. We also leave open the question of whether an isotropic parameterization exists. We review other probabilistic growth processes on grids, and describe qualitative and quantitative properties of the models. We also consider a deterministic growth model based on the diffusion equation, and show empirically that discretization of this model leads to a steady state configuration that appears to be polygonal.

9. Longin Latecki and Azriel Rosenfeld, "CP_3-Convexity: A Characterization of the Boundaries of Convex Sets." CAR-TR-690, CS-TR-3147, October 1993.

ABSTRACT: We call a set "CP_3-convex" iff, whenever it contains three *collinear* points p,q,r, it contains at least one of the line segments pq, qr, rp. CP_3-convexity is a special case of the P_3-convexity property introduced by Valentine, in which p,q,r are not required to be collinear. We show that a simple closed curve bounds a convex region in the plane, and that a simple arc is a subset of such a simple closed curve, iff they are CP_3-convex; this improves on results obtained over 30 years ago by Menger and Valentine.

10. Azriel Rosenfeld, "Fuzzy Plane Geometry: Triangles." CAR-TR-694, CS-TR-3175, November 1993.

ABSTRACT: A fuzzy triangle T (with a discrete-valued membership function) can be regarded as a nest of parallel-sided triangles T_i with successively higher membership values. Such a nest is determined by its max projections on any two of its "sides". The area (perimeter) of T is a weighted sum of the areas (perimeters) of the T_i's. The side lengths and altitudes of T can also be defined as weighted sums obtained from projections; using these definitions, the perimeter of T is the sum of the side lengths, and the side lengths are related to the vertex angles by the Law of Sines, but there is no simple relationship between the area of T and the products of the side lengths and altitudes.

11. David M. Mount and Nathan Netanyahu, "Efficient Randomized Algorithms for Robust Circular Estimation." CAR-TR-697, CS-TR-3198, December 1993.

ABSTRACT: The problem of fitting a circular arc to a finite collection of points in the plane is an important problem in statistical estimation having significant industrial applications. Recently there has been a great deal of interest in *robust estimators*, because of their lack of sensitivity to outlying data points. The basic measure of the robustness of an estimator is its *breakdown point*, i.e., the fraction (up to 50% percent) of outlying data points that can corrupt the estimator. One problem with robust estimators is that achieving high breakdown points (near 50%) has proved to be computationally demanding. In this paper we introduce *non-linear* Theil-Sen and repeated median (RM) variants for *circular arc estimation* (CAE), having (roughly) 21% and 50% breakdown points, respectively. We present two randomized algorithms, which run in $O(n^2 \log n)$ expected time and require $O(n)$ space. These algorithms rely on nonlinear generalizations of inversion counting, random sampling, and range searching.

12. Azriel Rosenfeld, "Image Analysis and Computer Vision: 1993." CAR-TR-698, CS-TR-3200, January 1994.

ABSTRACT: This paper presents a bibliography of nearly 1300 references related to computer vision and image analysis, arranged by subject matter. The topics covered include computational techniques; feature detection and segmentation; image analysis; two-dimensional shape; pattern; color and texture; matching and stereo; three-dimensional recovery and analysis; three-dimensional shape; and motion. A few references are also given on related topics, such as geometry, graphics, coding and processing, sensors and optical processing, visual perception, neural nets, pattern recognition, and artificial intelligence, as well as on applications.

13. Ehud Rivlin, Sven J. Dickinson and Azriel Rosenfeld, "Recognition by Functional Parts." CAR-TR-703, CS-TR-3222, February 1994.

ABSTRACT: We present an approach to function-based object recognition that reasons about the functionality of an object's intuitive parts. We extend the popular "recognition by parts" shape recognition framework to support "recognition by functional parts", by combining a set of functional primitives and their relations with a set of abstract volumetric shape primitives and their relations. Previous approaches have relied on more global object features, often ignoring the problem of object segmentation and thereby restricting themselves to range images of unoccluded scenes. We show how these shape primitives and relations can be easily recovered from superquadric ellipsoids which, in turn, can be recovered from either range or intensity images of occluded scenes. Furthermore, the proposed framework supports both unexpected (bottom-up) object recognition and expected (top-down) object recognition. We demonstrate the approach on a simple domain by recognizing a restricted class of hand-tools from 2-D images.

14. Azriel Rosenfeld and Angela Y. Wu, "Geodesic Convexity in Discrete Spaces." CAR-TR-705, CS-TR-3236, March 1994.

ABSTRACT: A pebbled graph is called "(geodesically) convex" if at least one shortest path between any two unpebbled nodes has no pebbles on any of its nodes. There exist conditions on the node neighborhoods in a pebbled graph that imply convexity; but no such conditions can be necessary for convexity. The convex pebblings can be characterized for various special types of graphs, such as cycles, trees, and cliques. For a graph L whose nodes are the lattice points in the plane under the relation of row or column adjacency, we show that a pebbling of L is convex iff the set of unpebbled nodes is connected and orthoconvex.

15. Zoran Duric, Azriel Rosenfeld and James Duncan, "The Applicability of Green's Theorem to Computation of Rate of Approach." CAR-TR-710, CS-TR-3273, May 1994.

ABSTRACT: The rate of approach (ROA) of a moving observer toward a scene point, as estimated at a given instant, is proportional to the component of the observer's instantaneous velocity in the direction of the point. In this paper we analyze the applicability of Green's theorem to ROA estimation. We derive a formula which relates three quantities: the average value of the ROA for a surface patch in the scene; a surface integral that depends on the surface slant of the patch; and the contour integral of the normal motion field around the image of the boundary of the patch. We analyze how much larger the ROA on the surface patch can be than the value of the contour integral, for given assumptions about the variability of the distance to points on the surface patch. We illustrate our analysis quantitatively using synthetic data, and we also validate it qualitatively on a real image sequence.

16. Azriel Rosenfeld, "''Geometric Properties'' of Sets of Lines." CAR-TR-724, CS-TR-3318, July 1994.

ABSTRACT: When we regard the plane as a set of points, we can define various geometric properties of subsets of the plane—connectedness, convexity, area, diameter, etc. It is well known that the plane can also be regarded as a set of lines. This note considers methods of defining sets (or fuzzy sets) of lines in the plane, and of defining (analogs of) "geometric properties" for such sets.

17. Zoran Duric, Jeffrey Fayman and Ehud Rivlin, "Function from Motion." CAR-TR-737, CS-TR-3355, September 1994.

ABSTRACT: In order for a robot to operate autonomously in its environment, it must be able to perceive its environment and take actions based on these perceptions. Recognizing the functionalities of objects is an important component of this ability.

In this paper, we look into a new area of functionality recognition: determining the function of an object from its motion. Given a sequence of images of a known object performing some function, we attempt to determine what that function is. We show that the motion of an object, when combined with information about the object and its normal uses, provides us with strong constraints on possible functions that the object might be performing.

18. Scott F. Thompson, "Growth Models for Shapes." CAR-TR-743, CS-TR-3367, October 1994.

ABSTRACT: A central problem in computer vision is to detect, delineate (segment) and recognize objects in an image. One reason why this is difficult is that very little information specific to given types of objects is used during segmentation. Making use of information about an object's shape, for example, should facilitate and improve the segmentation of that object. The thrust of this thesis lies in the development of models for shape that provide an effective basis for computer-aided recovery of natural, specifically biological, shapes. We introduce a 2D discrete growth model for shape from a point on a Cartesian grid, based on notions related to biological growth. By "growth" is meant an accretionary process occurring at the boundary of the shape. We discuss two types of growth models: probabilistic models and deterministic (periodic) models. A probabilistic model on the Cartesian grid, which associates probabilities of growth with each of the eight directions, is considered. While such models empirically have been shown to describe many natural growth phenomena, complete quantitative characterizations do not yet exist. We prove that a class of models of this type is not capable of generating isotropic shapes. We introduce a new type of deterministic growth model based on the notion of "time delay". Associating a delay with each direction defines a time delay kernel (TDK); we show that such kernels produce classes of convex octagons, and that sequences of TDKs can give rise to arbitrary convex polygons. We also show that growth in a (stochastic) environment of facilitators and inhibitors, which decrease or increase the time delays respectively, appears to describe biological growth processes. As an example, we present results which suggest that simple periodic growth

processes in an environment describe the gross morphology of multiple sclerosis lesions at the scale afforded by magnetic resonance images.

19. Azriel Rosenfeld, "Image Analysis and Computer Vision: 1994." CAR-TR-755, CS-TR-3400, January 1995.

ABSTRACT: This paper presents a bibliography of over 1900 references related to computer vision and image analysis, arranged by subject matter. The topics covered include computational techniques; feature detection and segmentation; image analysis; two-dimensional shape; pattern; color and texture; matching and stereo; three-dimensional recovery and analysis; three-dimensional shape; and motion. A few references are also given on related topics, such as geometry and graphics, compression and processing, sensors and optics, visual perception, neural networks, artificial intelligence, and pattern recognition, as well as on applications.

20. Zoran Duric and Azriel Rosenfeld, "Stabilization of Image Sequences." CAR-TR-778, CS-TR-3496, July 1995.

ABSTRACT: The motion of a vehicle can usually be regarded as consisting of a desired smooth motion combined with an undesired non-smooth motion that includes impulsive or high-frequency components. If the vehicle is carrying a camera, the non-smooth motion will perturb the sequence of images obtained by the camera. The goal of image sequence stabilization is to correct the images so that they are approximately the same as the images that would have been obtained if the motion of the vehicle had been smooth.

We analyze the smooth and non-smooth motions of a ground vehicle and show that only the rotational components of the non-smooth motion have significant perturbing effects on the images. We show how to identify image points at which rotational image flow is dominant, and how to use such points to estimate the vehicle's rotation. Finally, we describe two algorithms that fit smooth (piecewise constant) rotational motions to these estimates; the residual rotational motion can then be used to correct the images. We present results for an image sequence obtained from a camera carried by a ground vehicle moving across bumpy terrain; videos of several such sequences, before and after stabilization, demonstrate the effectiveness of our approach.

21. Azriel Rosenfeld and Chiao-Yung Sher, "Detecting Image Primitives Using Feature Pyramids." CAR-TR-782, CS-TR-3507, July 1995.

ABSTRACT: Primitive image parts of arbitrary sizes can be detected and extracted efficiently using local operations in a multiscale ("pyramid") representation of the image. This paper describes several multiscale methods of detecting blob-like image parts, and also discusses the problem of extracting ribbon-like image parts.

22. Scott Thompson, Azriel Rosenfeld and Satoshi Iwata, "Discrete Curvature-Based Contour Evolution." CAR-TR-810, CS-TR-3593 , December 1995.

ABSTRACT: An important problem in computer vision is the decomposition of a shape into parts (e.g., lobes or protrusions). Modeling the evolution of a shape's boundary as a real-valued solution to the reaction-diffusion equation has been shown to be useful for shape decomposition. Such methods rely on solving partial differential equations (PDEs) and must deal with the problem of singularities. In this paper, we describe a low precision discrete method, based on the 8-connected chain codes of the boundary and coboundary of the shape, that approximates the PDE-based methods and avoids the singularity problem. We also give examples of other (nonlinear) types of boundary evolution processes.

23. Azriel Rosenfeld, "Image Analysis and Computer Vision: 1995." CAR-TR-809, CS-TR-3600, January 1996.

ABSTRACT: This paper presents a bibliography of over 1550 references related to computer vision and image analysis, arranged by subject matter. The topics covered include computational techniques; feature detection and segmentation; image and scene analysis; two-dimensional shape; pattern; color and texture; matching and stereo; three-dimensional recovery and analysis; three-dimensional shape; and motion. A few references are also given on related topics, including geometry and graphics, compression and processing, sensors and optics, visual perception, neural networks, artificial intelligence and pattern recognition, as well as on applications.

24. Akira Nakamura and Azriel Rosenfeld, "A Theory of Digital Functions and their Basic Properties." CAR-TR-811, CS-TR-3601, January 1996.

ABSTRACT: "Continuous" functions on digital pictures is a concept introduced by the second author, who has studied various properties of such functions from a picture processing point of view. In this paper we propose a "digital" function theory which treats "continuous" functions, "derivatives" (including partial derivatives), and "integrals" of functions on digital spaces and establishes several of their basic properties. We also consider "digital" complex functions, which are functions from a two-dimensional (2D) space into a 2D space. We define "derivatives" of digital complex functions and establish modified Cauchy-Riemann differential equations and a Cauchy Integral Theorem analogous to those for standard complex functions. Finally, we make some remarks about the applicability of this theory to digital pictures.

25. Azriel Rosenfeld, ''Visibility of ''Tame'' Functions.'' CAR-TR-812, CS-TR-3602, January 1996.

ABSTRACT: Let $f(y)$ be a one-valued function defined on a finite interval I. We call f ''tame'' if it is continuous and piecewise convex or concave. If P is a point on or above a tame function f, we say that a point $Q=(x,f(x))$ of f is visible from P if the open line segment PQ lies above f. It can be shown that the points of f visible from P subtend an angular sector at P. Moreover, these visible points comprise a finite number of arcs of f, and each gap between these arcs corresponds to a different concavity of f; thus different subsets of the concavities can be regarded as defining different ''aspects'' of f as seen from points on or above f. It can also be shown that there exist finite sets of points P from which all of f is visible, but that this need not be true if the points are required to lie on f. The problem of extending these results to a one-valued ''terrain'' function defined on a planar region is also discussed.

26. Sandor Fejes, ''Migration Processes: Theory and Applications.'' CAR-TR-813, CS-TR-3603, January 1996.

ABSTRACT: Optimization processes based on ''active models'' play central roles in many areas of computational vision as well as computational geometry. Unfortunately, current models usually require highly complex and sophisticated mathematical machinery and at the same time they also suffer from a number of limitations which impose restrictions on their applicability. In this dissertation a simple class of discrete active models, called migration processes, is presented. The processes are based on iterated averaging over neighborhoods defined by constant geodesic distance. It is demonstrated that the migration process model—a system of self-organizing active particles—has the advantage of direct implementability and thus the potential of user interaction available in parametric active models (''snakes''), combined with the topology independence as with implicit (contour evolution) models, but without using higher dimensional representation. After establishing a mathematical framework for migration processes we analyze various properties of migrating sets and illustrate some of the potential applications of the approach. The processes can be applied to derive natural solutions to a variety of optimization problems, including defining (minimal) surface patches given their boundary curves; finding shortest paths joining sets of points; and decomposing objects into ''primitive'' parts.

Appendix B: Journal Publications

1. 3-D shape recovery using distributed aspect matching (with S.J. Dickinson and A.P. Pentland), IEEET-PAMI 14, 1992, 174-198.

2. Compact object recognition using energy function based optimization (with N.S. Friedland), IEEET-PAMI 14, 1992, 770-777.

3. Maximum-likelihood edge detection in digital signals (with S. Banerjee), Image Understanding 55, 1992, 1-13.

4. From volumes to views: An approach to 3-D object recognition (with S.J. Dickinson and A.P. Pentland), Image Understanding 55, 1992, 130-154.

5. Image analysis and computer vision: 1991, Image Understanding 55, 1992, 349-380.

6. Linear feature compatibility for pattern-matching relaxation (with P. Cucka), Pattern Recognition 25, 1992, 189-196.

7. Inexact Bayesian estimation (with M. Abdel-Mottaleb), Pattern Recognition 25, 1992, 641-646.

8. "Qualitative" Bayesian estimation of digital signals and images (with M. Abdel-Mottaleb), Pattern Recognition 25, 1992, 1371-1380.

9. MAP estimation of context-free grammars (with S. Banerjee), Pattern Recognition Letters 13, 1992, 95-101.

10. MAP estimation of piecewise constant digital signals (with S. Banerjee), Image Understanding 57, 1993, 63-80.

11. Image analysis and computer vision: 1992, Image Understanding 58, 1993, 85-135.

12. Model-based cluster analysis (with S. Banerjee), Pattern Recogntion 26, 1993, 963-974.

13. Evidence-based pattern-matching relaxation (with P. Cucka), Pattern Recognition 26, 1993, 1417-1427.

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